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INITIAL EVALUATION OF PRINCIPLES FOR GRAPHICAL DISPLAYS IN MAINTENANCE PROBLEM SOLVING

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This paper reports the findings of two studies of the use of diagrams for maintenance problem solving. One study involved a protocol analysis of one maintainer working three maintenance problems. The protocol was analyzed for actions performed, stategies employed, diagrams used, and the relationships among all three. These findings were then used to develop a view of the cognition involved and the information required for maintenance problem solving. With this foundation, we developed a general aggregation and abstraction principle for displays that would help maintainers solve maintenance problems. Displays were developed based on this principle and a second study was conducted to test the efficacy of these displays for maintenance problem solving. The second study involved six helicopter technicians solving problems using either standard diagrammatic materials or the proposed new display materials. The results showed that the

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ABSTRACT

This paper reports the findings of two studies of the use of diagrams for maintenance problem solving. One study involved a protocol analysis of one maintainer working three maintenance problems. The protocol was analyzed for actions performed, strategies employed, diagrams used, and the relationships among all three. These findings were then used to develop a view of the cognition involved and the information required for maintenance problem solving. With this foundation, we developed a general aggregation and abstraction principle for displays that would help maintainers solve maintenance problems. Displays were developed based on this principle and a second study was conducted to test the efficacy of these displays for maintenance problem solving. The second study involved six helicopter technicians solving problems using either standard diagrammatic materials or the proposed new display materials. The results showed that the experimental displays developed from principles of aggregation and abstraction provided significant reduction in actions required and information sought by maintenance problem solvers over conventional diagrammatic material. These findings suggest that using displays more closely matching the internal representations of technicians results in fewer cognitive actions being required for maintenance problem solving.

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INTRODUCTION

The purpose of this work is twofold. The first goal is to develop principles to guide the transformation of hardcopy formats of technical information to electronically displayed formats. The end-users of the displays will be maintainers of complex systems. The primary motivation in this transfer is the need to go from large blueprint sized hardcopy, often called C size, to small CRT display sized images. These external representations of maintenance information should support the internal representation and processing of the maintainer. There are three aspects of the use of this information that must be understood before such principles can be developed. One is the nature of the device being maintained. This component drives the other two by providing components, actions, and relationships that must represented or carried out. The second aspect is the nature of the information available and tasks carried out in the maintenance environment. Three is the nature of the knowledge and cognitive processes of the maintainer. The relationships among these are depicted in Figure 1.

Figure 1. Maintenance Domain Figure goes about here

The second goal of this work is to evaluate these display principles in a realistic context with maintainers of an operational system. The principles were used to generate displays in an actual maintenance domain. Then the displays were given to maintainers in paper form to use in real versions of their maintenance tasks. Since this analysis and evaluation resides in the larger context of attempting to understand and aid maintainers of complex systems, and since the work is being done with real maintainers, the results will be generalizable to a variety of maintenance domains.

BACKGROUND

Current work aimed at understanding the use of external representations in problem solving of any type might be summarized best by turning to Figure 2 which is a much simplified illustration of the general processes involved in cognition. This figure depicts a visual perception or understanding process (B) by which information is taken from an external representation (A) and produced in the form of an internal representation (C) that reflects the external world (veridical representation). It next depicts a concept formation process (D) by which the initial representation (C) is either translated, transformed, or re-constructed as a

relevant internal representation (E). Finally, it depicts a problem solving process (F) by which the relevant internal representation (E) is matched to some rule, model, or other form to generate new internal representations for continued processing or to generate an external, or motor, action.

Figure 2. General Cognitive Process goes about here

The work on use of external representations for perception and performance has produced many models of particular cognitive processes. One expects these models could predict how information taken in the form of an external representation would be used as an internal representation for problem solving. However, there is a crucial gap in the work on these models. Researchers and theorists at the perceptual input level (e.g., Feldman, 1984; Kosslyn, Flynn, & Amsterdam, 1989; Marr, 1982; McClelland & Rumelhart, 1981) tend to model representation and processing from external representation to an internal representation (i.e., from A to C). They assume that the internal representation veridically reproduces the external world. Researchers and theorists at the next level (e.g., Kieras, 1988; Larkin, 1989; Larkin & Simon, 1987) assume an appropriate, relevant representation at the problem solving process (i.e., from E to F). They do not, however, account for how the representation arrived in suitable form.

In terms of the general cognitive process described in Figure 2, little if any work explicitly covers the process of getting a representation from the veridical internal representation (reproduction of the external world) to the internal representation that is relevant to the maintainer's problem (i.e., from C to E). Yet, this is precisely where the problem lies for making external representations useful for problem solvers. The closest work falls under the rubrics of concept formation, concept coherence, classification, or categorization (e.g., Barsalou, 1984; Osherson & Smith, 1982). Several researchers and theorists in these areas are working on computational models of concepts (e.g., Lebowitz, 1986; Michalski & Stepp, 1983; Smith, Osherson, Rips, & Keane, 1988); but, no one in those areas seems to be developing, applying, or testing the models in goal-directed activities such as problem solving in an attempt to bridge this gap in the general view of cognitive processing.[1]

For example, Larkin and Simon (1987) apply a recognition mechanism which assumes the user has a more or less exact representation already stored of what they are seeing. Kieras

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1 There has been some work by theorists such as Rumelhart and McClelland (1986) on concept acquisition, and by Kotovsky and Fallside (1989) on transfer. We suspect Kotovsky and Fallside would disagree with our view since they conclude that "it is the internal representation of a problem that determines transfer, and this representation can operate independently of the stimulus features. (p.105)". Our view is that the formation of an internal representation or concept always depends, at some level, on the stimulus features of the problem. That is, the maintainer creates or adapts the internal map to address the problem at hand.

(1988) improves on this slightly by invoking retrieval mechanisms thereby implying some construction or transformation process may occur. Recognition or retrieval is certainly one way our processing system works and is very efficient computationally. However, recognition and retrieval work alone only in a limited number of cases and conditions. Complete bridging will require additional mechanisms for transformation or construction of representations during the process of forming the relevant internal representation for the problem solving process.

CONCEPT FORMATION PERSPECTIVE

We need to determine how to transform very large schematic diagrams into useful computer screen size (5-9 inch, 12.70 - 22.86 cm diagonal) displays for use by maintainers of complex systems. Shrinking the diagrams to screen size is an inadequate solution since the complexity of the current diagrams does not translate well into very small screens. Instead we must reconstruct the diagrams so they are aligned with the information requirements of the maintainer. These information requirements are likely to be dynamic, based on the wide variance in user experience and nature of the maintenance task.

During problem solving (in this case maintenance problem solving), the problem solver seeks information from various sources. The context of the problem guides the search for that information. The problem solver must "transform" externally provided information into internally maintained conditions for problem solving (whether it is rule-firing or network-activation; whether it is procedure-based or model-based). We hypothesize that there is an active concept formation process which produces the transformation from external representation to relevant internal representation.

One plausible mechanism in this concept formation process is structure-mapping (Gentner, 1983, 1989). Gentner has proposed structure-mapping as a computational mechanism by which analogous concepts are recognized or formed. In the case of maintenance problem solving, structure-mapping as a concept formation process would take externally supplied information and try to map it to the set of possibilities that are the internally maintained conditions for problem solving in the current context. When there is not a direct mapping then a next best or analogous mapping could be made so the problem solving process could continue.

Structure-mapping can be operationally defined as judging the similarity of a target stimulus to a base stimulus through the dimensions of a similarity space. Gentner defines a similarity space composed of two dimensions. These dimensions are: 1) shared features and, 2) shared structure (relations among features). This view has a good foundation starting with the work of

Tversky (1977). However, there is a fundamental weakness in its development. The definition of structure mapping provides no means for defining what are features (and how to count them) and what are relations (and how to count them). We propose that the definitions of features and relations are dependent on the purpose of defining them. If our purpose is to use features and relations as a way of defining the similarity space between base and target stimuli in a maintenance domain then there must be an objective means for defining these entities. One means is to use the informational and behavioral characteristics of operational and maintenance environments as defined by Rasmussen (1983,1986).

Rasmussen suggests that operational and maintenance problem solving is characterized by three general classes of cognitive activities which operate on representations of information. The classes of cognitive activities are characterized by skill-based, rule-based, and knowledge-based problem solving. Representations are characterized by their location in a space defined by two dimensions: aggregation and abstraction. According to this view, different representations are used differently for different classes of activities depending on the information available and the sequence of processes leading to the current state. Furthermore, those representations may be operationally defined by their position in the aggregation by abstraction space. Operationally, this means that structure-mapping as a cognitive process should trigger different overt behaviors depending on the match between external information and internal representations. Both sets of these representations can be defined according to their position in the aggregation by abstraction space. This allows us to manipulate external representations according to this space. Consequently we should be able to determine the effect of different representations on the maintenance problem-solver's cognitive process and subsequent performance.

We propose the different uses of external representations are due to the differing information required, concepts formed, and cognitive problem solving processes engaged. In particular, we propose that the active concept formation mechanism of structure mapping is the primary determiner of the utility of external representations. One means for supporting structure-mapping is to define external representations that take advantage of the capabilities of the mechanism. Defining external representations according to levels of abstraction and aggregation at which the representations within the current problem solving process exist should facilitate the structure-mapping from external representation to relevant internal representation. If we develop a range of displays which covers the complete abstraction by aggregation space then we should support the problem solver no matter the level at which he or she is working.

In the following studies, we explore the abstraction by aggregation information space and the cognitive processes relevant to maintenance problem solving in a real-world domain. In the first

study we developed a cognitive framework for maintenance problem solving and concept formation based on observation of a subject matter expert solving maintenance problems. Using the results of the first study as a guide, we developed initial principles for displays based on information needed, concepts formed, and cognitive processes employed during maintenance problem solving. Then, for the second study we used these principles to further refine the framework, explore the relationship between concept formation and maintenance problem solving, and develop and test displays to be used during maintenance problem solving.

STUDY ONE

OBJECTIVES

The objective of this study was to develop a general domain model for maintenance problem solving for the SH-3 helicopter bladefold system. Development of an initial framework for cognition in maintenance problem solving, and an initial aggregation by abstraction framework for information needed and concepts constructed during maintenance problem solving were also objectives.

The general definitions evolve from Rasmussen (1983, 1986). Constrasting Rasmussen's rule-based and knowledge-based behavior with current cognitive views of problem solving (e.g., Greeno & Simon, 1988; Jones & Langley, 1988), we are led to reconsider the definitions of these classes of problem solving. According to traditional cognitive views, rule-based problem solving as a procedure based problem solving process can stand as defined by Rasmussen. Knowledge-based problem solving, however, might be defined better as model-based problem solving which corresponds more closely to views of problem solving as a form of model execution to generate and test hypotheses (White & Frederiksen, 1988, 1989).

For our purposes, an important contributor to the variability in the different kinds of problem solving is the match of the information provided for task performance to the information needed for the cognitive activities required for performance. Rasmussen defines the relevant dimensions of this information as level of aggregation (kinds of features) by level of abstraction (kinds of relations). The match is made through a structure-mapping mechanism according to a similarity judgment.

We propose that Rasmussen's definitions for aggregation by abstraction are appropriate operational definitions for Gentner's similarity space definitions; and, that behaviors generated by rule-based and model-based problem solving are differentially affected by information

displays represented at different places in this two-dimensional space. We expected to see this in observations from this study.

METHOD

The general method was a think-aloud protocol study in which a subject matter expert was asked to work through 3 problems in each of two ways (rule-based problem solving and model-based problem solving). The protocols were analyzed for actions taken, information used, and the relationships between actions and information.

Participant

The participant (M) was an aviation mechanic with over 15 years of experience performing and teaching maintenance troubleshooting in various environments. Although M never worked in the SH-3 helicopter environment, he had attended the training school for SH-3 bladefold. He also served as the knowledge engineer for a research project to develop an intelligent tutoring system authoring environment which used the SH-3 as its domain example.

Materials

Materials were three SH-3 bladefold maintenance problems, the SH-3 maintenance manuals relevant to bladefold maintenance problems, and protocol transcription sheets.

Procedure

The experimenter (E) had M think aloud while working each of three problems from the training course in which he had participated. During the protocols, E wrote down the verbal material that M generated[2]. During this process, E tracked all actions M performed, all information sought, all symptoms dealt with, and all solutions obtained. E and M held post-hoc discussions to clarify the protocols. During that process, E and M also identified all relevant objects by talking through and examining all diagrams; and, identified all actions/tasks by talking through and examining all procedures. Finally, E and M identified all sources of information by talking through and examining the manuals as they were used in the problem solving process.

2 These are not verbatim transcripts of M's think aloud process. They are a capture of some verbatim quotes, some phrases, and some summaries of M's process.

M worked each problem twice. First he worked it using the fault tree provided in the maintenance manual. This provided the rule-based version of the problem solving process. The second time he worked the problem using the models he had learned in the training course. This provided the model-based version of the problem solving process. This process yielded 6 protocols. Of course there are obvious limitations to this method but it served well as a tool to generate the initial framework to test later on experienced maintainers.

RESULTS

The results of this study are split into two components. One set of results addresses the goal of developing a cognitive framework for maintenance problem solving. The other set of results addresses the goal of illuminating the information needed and concepts formed during the maintenance problem solving process, especially in the context of the abstraction by aggregation information space.

Cognitive Framework

Data. The data used to develop the initial framework were the statements M made and the diagrams M examined during each problem solving session. These were carefully tracked and recorded so they could be used to reconstruct M's problem solving process later. After reconstructing the problem solving process, E and M went through each protocol to guarantee its correctness. The protocol statements were then used to identify cognitive tasks, information used, and the relationships among them.

Findings. Our initial analyses of the protocols collected from M show eight tasks that maintainers perform in the pursuit of their duties. They are listed here and are discussed further in the following paragraphs:

1. look
2. identify
3. match
4. reason
5. remember
6. locate
7. repair
8. test

The distribution of the tasks among the two approaches to solving the maintenance problem and the three problems is shown in Table 1. The numbers are interesting but, given that they were derived from one maintainer, should not be given too much weight. The only striking

observation from the table is the high frequencies of tasks *locate, look, remember*, and *test* compared to the others.

Table 1. Task Distribution goes about here

The task of *look* refers to the act of visually acquiring information about some state or relation. In reference to our general processing model (Figure 2), this action reflects the visual understanding process transforming an external representation into a direct perception or veridical representation. For example, M would "look in the technical manual for problem condition in decision tree." Or, M would "look at the Blade Fold System Location Diagram to find information about the location of P111." Or, finally, M would "look at [a diagram] to find the parts relevant to a part of interest." In each of these cases M is examining an external representation of some aspect of the current problem.

The task of *identify* refers to the formation of an internal representation to reflect some state of the external world or the problem solving process. In reference to Figure 2, this action reflects the concept formation process transforming from C to E. For example, *identify* often referred to confirmation of the problem condition that needed to be addressed by the maintainer. In such cases it was usually referred to by M expressing a need to see the indications of the problem for himself. For example, he would "identify the problem condition by confirming the reported problem using a procedural checklist". It could also refer to confirmation of some device element as being part of some component. For example, M reported "identifying the limit switch as part of the control lock cylinder". In either case, identify refers to representing the condition(s) of the current problem.

The task of *match* refers to finding an equivalence between a set of problem conditions and some aspect of either a rule or a model. In reference to the general cognitive model, this action reflects activity in the problem solving process. In the case of rules, there were an explicit set of rules provided for the maintainer to use in attaining solutions to problems. So the match was between the problem conditions and the antecedent clause in a rule (or the first in a chain of rules). For example, M matched the initial condition of *blade-positions-but-will-not-fold* with TROUBLE #17 in the fault tree. In the case of models, M was usually trying to generate a match between a state produced by some causal relationship and the problem conditions provided. For example, M matched the model generated *blades-folded-and-no-lights-means-bad-light-OR-means-bad-connection-between-slip-rings* to the initial conditions of *blades-folded-blade-folded-light-does-not-go-on*. In each of these examples, M is comparing one representation of the system to another representation of the system in search of a match. At the

same time, though, there also appear procedural rules in the middle of this model-based processing. For example, while reasoning about the relation of limit switches to blade fold, M matched and executed a procedure for a test of limited relevance to the problem.

The task of *reason* refers to a process by M that appears very much like deductive logic. This action also refers to activity in the problem solving process. For example, M used his model to reason as follows:

> "...between slip ring 6 and slip ring 2 there is a switch for each blade. The blade rests on the switch when the blade is folded. So, either a switch is broken or a wire is broken between slip ring 6 and slip ring 2. So, test each switch and the wires between each switch."

In this example, as in a few others, M is relying on his ability to understand and think logically about the data at hand.

The task of *remember* refers to M attempting to "remember a representation that he had already looked at", "remember a model from which to match or reason", or "recall a rule that matches some aspect of the current condition". In reference to the general cognitive process model this denotes the process of retrieving from memory a relevant representation. Whether this remembered representation is constructed via a concept formation process or retrieved directly by a problem solving process is probably dependent on the situation.

The task of *locate* refers to specifying and reaching the location of some particular element of the device. In Figure 2 this refers to the action resulting at G. During this study, it was usually referred to by M expressing a simple action in response to any diagnosis made that required a test. For example, upon deciding that the first test in a problem is to check the voltage at pin D of connector P111, M would report needing to "locate or find P111".

The tasks of *repair* and *test* referred to the physical activities associated with each. They also reflect actions resulting at G. Examples of these are "test P111 for power", "test a limit switch to see if it opens and closes", and "replace a bad wire in P110-E".

Closer examination of the protocols also shows patterns to the execution of these tasks by M that correspond to the distinction among rule-based and model-based problem solving.

Rule-based processing was characterized by a cycle of *identify-match-locate-test* followed by a *repair* or *replace* after the final test. An example from the protocols in problem 2 follows:

IDENTIFY problem condition - blades will not position, no blade spread light
LOOK in manual for problem condition

MATCH problem condition to rule - find match at trouble #1
LOCATE element named in consequent - blade fold circuit breaker CB80
TEST element - circuit breaker CB80

.
.
. (cycle through until desired test results obtained)
.

REPAIR/REPLACE (diagnosis incomplete on this particular problem)

As shown, the occurrence of the pattern of responses that characterizes rule-based processing is intuitively plausible. Identify produces a representation that will be compared directly to the representations of rules by match. A similarity judgment might determine that a transformation is needed before the match can be made but the general cycle holds up well.

Model-based processing was characterized by a cycle of *identify-remember-match-reason-locate-test* followed by *repair* or *replace* after the final test. An example, from the protocols in problem 1 follows:

IDENTIFY problem condition - blades fold, blades folded light does not go on
REMEMBER training model
MATCH condition to training model
REMEMBER ....
LOCATE slip rings

.
.
.

REASON about model - "Between slip ring 6 and slip ring 2 there is a switch for ...."

.
.
.

TEST element - P111-D

.
.
. (cycle through until desired test results obtained)
.

REPAIR/REPLACE wire

This pattern of responses supports the notion that model-based processing occurs. Identify produces a representation that is compatible with some aspect of a functional model in the blade fold system. This allows M to deductively reason about causal relationships concerning those elements identified in the problem condition. As shown, such reasoning allows M to reach a

repair action in fewer "cognitive steps" than the rule-based processing allows. This is desirable, however, model-based processing also provides more room for error.[3]

Information & Concepts

Data. The data are the particular diagrams and pictures M examined, the reasons he examined them, and the actions he was carrying out when examining them.

Findings. As described earlier, we are starting with an abstraction by aggregation framework for representing the maintenance object domain. The problem solving protocols with M supported the use of that framework for representation. M showed a decided tendency to move explicitly among well-defined levels of the aggregation dimension when closing in on a possible cause of a problem. He also used aggregation to find out where objects were located, what they were connected to, and what they were parents or children of. These relationships provide an initial set of relationships for the aggregation dimension of the domain representation.

In both rule-based and model-based processing, M tended to start with a system level description or diagram and move successively toward a component or element level description or diagram. For example, during rule-based processing on one problem, M selected the decision tree, then the relays, then the general system diagram, and then a unit diagram that is a subset of the general system diagram.

These findings about the aggregation dimension lend themselves to the development of a device representation based on aggregation. Such a representation will include objects described at a system level (e.g., *accessory-drive-system*, *automatic-blade-fold-system*, *auxiliary-flotation-system*, etc.). Within each system there are numerous units which are clearly defined (e.g. for the automatic-blade-fold-system we can define *blades*, *rotary-wing-head*, *blade-positioning-system*, etc.). Within each unit there are numerous components that are clearly defined (e.g., for the blade-positioning-system we can define *blade-positioner-hydraulic-motor, linear-actuator, pressure-switch-P237*, etc.). Finally, for each component we can define numerous elements such as *wire-x*, *pin-y*, *other-feature-z*, etc. For current purposes, the entities in this representation can have any combination of the following relationships with each other: *is-element-of*, *is-connected-to*, *is-located-at*.

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3 The way to reduce error and steps is to increase skill-based processing. Although we will not deal with this issue here, it is important to note that the transformation from model-based and rule-based processing to skill-based processing is a transformation of elements and relationships into features that are directly perceived and responded to. We might expect that the transition to skill-baseD will actually be accomplished by the generation of rules from the model which are internalized by M and not available for "direct inspection".

The actions of M on the abstraction dimension are not as clear but still lend support to the use of levels of abstraction as a representational form for the maintainer. Rasmussen has defined levels of abstraction according to purpose, function, and form. Applying his definitions to display development yields diagrams or displays with specific characteristics at each level. At the purpose level of abstraction, displays maintain relationships depicting the purpose of components within a larger system, ie., a theory of operations for a device. At the function level of abstraction, displays maintain relations depicting input-output relationships of components with respect to each other, ie., flow diagrams and schematic diagrams. At the form level of abstraction, displays maintain physical relations among different components with respect to each other, ie., the physical look or location of a component.

During the problems that M worked, he generally started at the level of form to identify the location of the element of interest. However, he only used diagrams at a functional level when he was doing model-based processing. And, he typically only used one diagram per problem. This could be an artifact of the simplicity of the problems that M worked. If problems are developed that have interacting functional systems, then the maintainer may be forced to explore more system or device functions or even purposes (reflected in theory of operations) and, consequently, use multiple levels of abstraction and/or aggregation..

When M did use external representations that varied on the abstraction dimension, he seemed primarily interested in determining some aspect of a functional relationship. For example, he looked for what source provides power in a circuit or what provides a signal to a location. These relationships will provide an initial set of relationships for the abstraction dimension of the domain representation. In particular, we can represent *is-element-of, gives-power-to, gets-power-from, gives-signal-to*, and *gets-signal-from.*

Developing a representation along the abstraction dimension requires defining entities at the level of form, function, and purpose. The representation described above is the representation at the level of form. Now, at the level of function, we can define entities under the automatic-blade-fold-system such as *accessory-drive-control-unit, blade-fold-circuit-schematic*, etc. These functional units are decomposable through component levels to an element level that should define elements the same as elements at the form level of representation.

DISCUSSION

This study produced three significant findings that bear on the original hypothesis and the plan for Study Two. One was the initial cognitive framework derived from the maintenance

problem solving protocols. This framework provides a beginning characterization of the cognitive activities required for maintenance problem solving. With regard to the discussion of the general cognitive process in the introduction, it is particularly interesting to note the importance of several of these tasks. For example, several tasks such as *identify*, *match*, and *reason* are likely to require a mapping between some external representation of an aspect of the problem and some internal representation of a rule or model or state knowledge necessary for problem solving.

Another finding was the value of the aggregation by abstraction space in describing the external representations used by this maintainer. This space not only captured the information he used but provided differential characterizations according to particular tasks this maintainer was carrying out. For example, M tended to use diagrams at the form level of abstraction and vary level of aggregation as a means for locating components and systems. It appears that these representations match his natural representations of the system surface features and physical relationships very well. In Study two we exploited these tendencies to see if they held up in a larger sample of maintainers.

In another example, M tended to use diagrams at the function level of abstraction and the sub-system and circuit levels of aggregation to determine some aspect of a causal relationship. These were primarily carried out when M was engaged in model-based problem solving. It appears that these levels of representation are particularly well matched to this participant's model representations of the system. This is not a completely surprising result since the training that he underwent included models of physical function. Not all maintainers get this training -- hence, we were interested to see how well this finding held up in Study Two.

A third finding was that model-based problem solving tends to contain internal cycles of rule-based processing. The existence of these cycles, their relation to display use, and their relation to the rest of the problem solving process is difficult to uncover. It was necessary in Study Two to look for evidence of this to further illuminate its relation to information use in maintenance problem solving.

STUDY TWO

OBJECTIVES

The primary objective of this study was to develop and test initial principles for displays based on information needed, concepts formed, and cognitive processes employed during maintenance problem solving. Our general principle (and experimental hypothesis) is that

displays developed to cover the abstraction by aggregation information space will cover the range of possibilities of external representations needed for problem solving. Consequently, the maintenance problem solver should be able to find displays that closely matches his or her own problem representation and therefore solve problems more efficiently. The actions taken are driven by the concept formation process trying to map the external representation to the representation needed for problem solving. The displays needed are those examined in an effort to generate the mapping. The measure of success for this test is the extent to which the maintainer using principled displays demonstrates a savings in actions and/or displays needed to solve a problem. This savings would be over the actions and/or displays needed to solve the problem using standard maintenance procedures and diagrams which have only a limited organizational structure.[4]

Another objective of this study is to further refine the cognitive framework for maintenance problem solving begun in Study One. In the earlier study we outlined a set of tasks that maintainers typically engage in during problem solving. We expected to refine this characterization based on the problem solving activities of this study's participants. In Study One we also described the way in which different tasks seemed to relate to information at different points in the aggregation by abstraction space. Further, we described the role of different kinds of information for different problem solving strategies. In this study we wanted to be able to specify whether the particular relations among representations of information (in the aggregation by abstraction space) and cognitive activities and strategies hold up across several maintainers and multiple problems. With regard to the strategies employed, we wanted to further clarify the mix of rule-based processing that appears during predominantly model-based problem solving.

Our test of the general principle and further refinements to the cognitive framework were designed to provide results that would either cause us to reconsider the current view or, yield insight into more detailed views of the relationships among cognitive activities and concepts represented in the abstraction by aggregation space. If the general principle was supported, we further planned to identify such relationships in this study.

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4 It should be noted here that success for the purpose of providing small displays only requires that maintainer problem solving performance using principled materials be at least as good as that of the problem solving performance using standard practices and materials.

METHOD

The general method was a think-aloud problem solving session in which each participant was given three SH-3 bladefold maintenance problems to solve. In support of this problem solving each participant was given either standard materials or the principled materials we had developed. They were asked to think through the problem aloud. The protocols were analyzed for actions taken, display materials used, strategies employed, and the relationships among cognitive activities and information used.

Participants

The participants were six SH-3 helicopter maintenance technicians in the U.S. Navy. Three of these maintainers were relatively inexperienced. This is best illustrated by the fact that they worked six of nine problems with a rule-based problem solving process (3 participants, 2 of 3 problems each). The other three maintainers were relatively experienced. This is best illustrated by the fact that they worked all problems with a model-based problem solving process.

Materials

Pre-test materials consisted of a verbally presented five minute explanation and collection of demographic information. This explanation outlined the purpose of the study and the procedure participants were to follow. Participants were told they could find out details about the study after completing the problem solving sessions. The demographic information was used to define the levels of experience of each maintainer in the study.

There were several items in the problem solving materials. Those items relevant to the study tasks were the three SH-3 helicopter bladefold problems and the graphical materials supporting each problem (standard materials for one problem and principled materials for two problems). Those items relevant to the experimenter's tasks were transcription sheets for recording actions taken and materials examined, a tape recorder for recording the problem solving sessions, and evaluation forms for the participants to evaluate the principled materials they had used for problem solving.

Graphical materials based on aggregation by abstraction principles were developed for all three of the problems. The three levels of aggregation employed were system, sub-system, and circuit. In the SH-3 bladefold domain, examples of systems are BLADES FOLD, BLADES SPREAD, and BLADES POSITION. Sub-systems of the BLADES FOLD are BLADE-

SEQUENCE, BLADE-LOCK, and BLADE-FOLD. A circuit of the BLADE-FOLD sub-system is the BLADES-FOLDED CIRCUIT. Examples of each are shown in Figure 3.

Figure 3. Example of levels of aggregation goes about here

The three levels of abstraction employed were form, function, and purpose as defined by Rasmussen (1986). For these materials, graphics at the form level of abstraction maintained all the physical relationships among the entities. This made it possible to see what the components looked like and where the components were located in relation to other components in the same system or circuit at the same level of aggregation. Graphics at the function level of abstraction maintained the relationships describing the physical functions components carried out with respect to one another. This made it possible to determine how systems worked and how they affected one another. Graphics at the purpose level of abstraction maintained the general operational relationships that components had with one another. This made it possible to determine what systems affected one another and what purposes they accomplished in so doing. Examples of each are shown in Figure 4.

Figure 4. Example of levels of abstraction goes about here

Procedure

We developed three problems for the maintainers to solve. Each problem was developed in cooperation with a subject matter expert from the Navy. The expert concluded that the problems were all reasonable, about the same difficulty, and would require close to the same skills and knowledge to solve. We created supporting display materials relevant to each problem at each of three levels of aggregation and abstraction. This produced a minimum of nine graphical displays per problem.

We presented one problem to one maintainer at a time. Each participant was asked to think aloud as he worked through the problem to solution. Participants were told they could work the problem using whatever strategies and procedures they normally would, with one constraint -- on two of the problems they could only use the display materials we provided. On the third problem, standard maintenance material was available.

All participants received the three problems in the same order. This was required for two reasons. One was to make sure that we could directly compare different participants on the same problem for similarities and differences in actions and strategies. The other was to make sure

these maintainers worked the standard materials problem first so that problem solving process would not be affected by having had exposure to the principled materials. Consequently, participants worked the first problem using standard materials.

After completing the first problem using standard materials, each participant was taken through the problem again by the experimenter (E). During this pass, E used principled display materials to show the maintainer how such displays might have been used to work the problem. This was done to familiarize the participant with the display concepts they were going to see in the subsequent problems.

During the second problem, principled display material was available and the participant was required to work the problem by starting with the material at the function level of abstraction. During the third problem, principled display material was available and the participant was required to work the problem by starting with the material at the purpose level of abstraction. As it turned out, participants primarily moved between form and function levels of abstraction. They generally found the purpose level of abstraction to be good for supporting their views but not for developing hypotheses or solutions.

After working the problems to solution, each participant was asked to make judgments about the display materials they had used. These judgments were made in response to a series of questions the experimenter asked. The questions were derived from Smillie, Nugent, Sander, & Johnson (1988).

RESULTS

The results of this study are presented in three components. The first considers the maintenance technicians' protocols to further refine the cognitive framework and the information space used in concept formation by these maintainers. During this protocol analysis, the actions of the protocols were coded to be used for analysis in the second component. The second component of the results takes the data extracted from the protocols and evaluates the displays used during the maintenance problem solving sessions. The third component of the results explores the relationships among cognitive actions for concept formation and problem solving.

Cognitive Framework

Data. The data used to further develop the cognitive framework were the statements each maintainer made during the problem solving sessions and the diagrams they examined at each

step of problem solving. Each statement was coded to reflect a cognitive action (or more than one action) in which the maintainer was engaged. The coding and the diagrams were used to reconstruct the problem solving process that each maintainer went through for each problem worked.

__Findings__. Initial analyses of the Study Two protocols provided reorganization of the tasks defined in Study One. We identified three general cognitive processes of the maintainers. In addition we identified five specific cognitive actions that maintainers carry out in support of those processes. These processes and actions are used to code the final versions of the participant protocols for the data analysis in the next section. The processes are:

1. locate
2. reason
3. test

The actions are:

1. look
2. identify
3. match
4. recall
5. goto
6. apply

There were other possible processes and actions for which we have evidence. However, they did not appear often enough to be distinguished from one of the above. Examples of some of the possible alternatives are *trace* and *repair*. The importance of these can only be determined with future studies.

Definitions of most of these were provided in the results from Study One. The following paragraphs will define those processes and actions which are changed or were not previously defined.

Goto refers to the physical actions required to actually change locations. In reference to the general cognitive process model of Figure 2, this reflects an action resulting at G. This can occur in the sense of the maintainer moving his or her body from one room to another; or, it can occur in the sense of the maintainer moving his or her hand from one page of a manual to another.

Apply refers to carrying out the actions embodied by the use of some rule, model, or test procedure. In reference to the general cognitive process model of Figure 2, this also reflects an

action resulting at E. In these protocols, apply most often referred to the actions of carrying out a test on particular components of the system.

Locate has the same definition provided in Study One. It has now taken on the added significance of being considered a higher order process which is carried out by a set of actions. This is also true of *reason* and *test* described in the following paragraphs. As higher order processes, they generate cycles of action patterns that would be represented in the general cognitive process model of Figure 2 as multiple stages with feedback loops. For example, *locate* usually consisted of a *look-identify* cycle followed by a *goto* (the stop rule on the *goto* would typically consist of an *identify-match* cycle). The *look* results in visual understanding which provides input for the *identify* which results in concept formation. This, in turn, provides feedback to visual understanding for the next *look*.

Reason has expanded from its definition in Study One. It can refer to a variety of cognitive action patterns which might characterize a deduce-and-conclude strategy, a hypothesize-and-test strategy, a match-rule-and-fire strategy, an apply-model-and-test strategy, or some other strategy. In this study, the most common patterns were a procedural rule-firing strategy and an apply-model-and-generate-hypothesis strategy. As such it usually consisted of either a *match-apply-recall* cycle in the case of model use or a *match-identify* cycle in the case of rule use.

Test typically refers to the process by which the problem solver might *apply* a test, *identify* a result, *match* the result to a test condition, and *identify* the next step. This can vary depending on the particular strategies the problem solver brings to the setting. Our study does not show any vastly different variations on this cycle.

Examination of the coded protocols show support for the finding from Study One that problem solvers choose functional level diagrams when doing model-based reasoning. This was true even when maintainers were given purpose level diagrams initially and asked to try to solve the problem.

Questioning of these maintainers showed that they felt the purpose level diagrams could be used to support their views of how the system worked. Further, the diagrams could be used for teaching people how the system worked. However, they could not be used to generate hypotheses about particular physical states of the system. Given this, we expected maintainers to use the purpose level diagrams to generate a hypothesis about relationships among components before going to function level diagrams to complete the problem solution.

Only two participants formulated hypotheses based on the purpose level diagrams. Two others discounted them altogether while the final two chose not to use them. It may turn out that purpose level diagrams are only useful for a general process such as *understand.* However, we saw no evidence among these maintainers of the need for such a process during problem solving.

The protocols also support the finding from Study One that problem solvers use form level diagrams along all levels of aggregation when *locate*-ing some system, circuit, or component. This was true of every maintainer. Upon questioning after the session, each person mentioned it was much easier to find locations of and relations between systems, sub-system, circuits and components using the levels of aggregation as an aid. They all said that it would help their work tremendously to have available materials arranged by level of aggregation alone.

Display Principles Evaluation

Data. The data were extracted from the protocol analyses. In particular we intended to examine the numbers of actions needed to solve a problem, the numbers of looks at displays needed to solve a problem, the numbers of different displays needed to solve a problem, and the numbers of errors committed during problem solving. It turned out that very few errors were committed by these maintainers. Consequently, errors are not considered here.

The data used are briefly defined in Table 2 and described below:

Table 2. Data definitions table goes about here.

Continued development of the cognitive framework yielded two levels at which cognitive activities can be examined. One level is that of cognitive processes. These refer to general cognitive processes such as *locate, reason,* and *test.* So, one set of data that we examined consisted of the numbers (frequency counts) of general cognitive processes each maintainer employed to solve a maintenance problem.

The other level at which cognitive activities can be examined is that of cognitive actions which make up processes. The general cognitive processes are made up of specific cognitive actions such as *match, identify,* and *look.* As discussed earlier, there is not a fixed number of actions per process; instead there may be different actions at different times or there may be recursive actions. Consequently, the measures of process and actions indicate different levels of

effort involved in the problem solving process.[5] The second set of data we examined consisted of the numbers (frequency counts) of the specific cognitive actions each maintainer employed to solve a maintenance problem. The third set of data we examined were the numbers and kinds of displays examined by the maintainers during their problem solving sessions.

The following analyses compare the numbers of cognitive processes, cognitive actions, and displays examined to solve maintenance problems. This presented a problem since we wanted to compare results from one problem to another. Each problem had a different number of processes, actions, and displays that were ***needed according to standard procedures*** to obtain a solution. To account for this difference we transformed each raw frequency into a proportion of the baseline actions that were needed to solve that particular problem according to standard procedures in the troubleshooting manual.

To create baselines for each problem, we worked each problem according to the troubleshooting chart in the SH-3 maintenance manual. We transcribed every action and display that was required to solve the problem according to the manual. We then divided each raw frequency score by the baseline to produce a proportion of baseline score. For example, Participant 1 employed 13 cognitive processes to solve the first problem using standard materials. The baseline number of cognitive processes needed for the first problem was 16. This yielded a proportion of .81. Participant 1 was able to solve the first maintenance problem using the experimental displays by resorting to only 81% of the number of cognitive processes they would have used with standard procedures.

Findings. These findings assess the value of the principled displays, in general, as support for the maintenance problem solving process. It is important to remember that we only examined data from six maintainers. Consequently, the results from the following ANOVAS are based on a small N.

There were four analyses conducted to evaluate how well principled displays served to support the problem solving process of these maintainers. Each was an ANOVA comparing the mean proportion of baseline scores for principled material presentation to the mean proportion of baseline scores for standard materials presentations. This is the MATERIALS variable. It has three levels - 1) standard materials; 2) principled materials, function level seen first; 3) principled materials, purpose level seen first. The other grouping variable is EXPERIENCE - 1) experienced; 2) not experienced. The mean scores by variables for cognitive processes, cognitive actions, and displays examined are listed in Table 3.

5 This may have implications for work such as the cognitive load work of Sweller (1988).

Table 3. Mean scores goes about here.

The first analysis examined the value of these displays for decreasing the frequency with which general cognitive processes were employed in problem solving. We analyzed the scores according to experience level and principled material presentation (EXPERIENCE x MATERIAL; 2 x 3 ANOVA). This analysis produced significant main effects but no interaction effects. The mean proportion of baseline scores for general cognitive processes used when problem solving with principled materials are significantly different from the proportion of baseline scores when using standard materials [$F_{(2,12)} = 5.038$; $p = .026$]. Figure 5 illustrates this difference and shows that the decrease in frequency of use of cognitive processes is greater for principled materials than for standard materials. This analysis also showed the mean proportion of baseline scores for experienced maintainers ($M = .422$) tend to be better than the mean proportion of baseline scores of inexperienced maintainers [$M = .907$; $F_{(1,12)} = 15.122$; $p = .002$]. These maintainers, when using principled materials, used general cognitive processes only .40 to .71 as often as required by baseline. When using standard materials, these maintainers use general cognitive processes .88 as often as the baseline procedures required.

Figure 5. Graph comparing the means of materials by experience level for cognitive processes goes about here.

The second analysis examined the value of these displays for saving on the number of specific cognitive actions employed in problem solving. We analyzed the scores according to experience level and principled material presentation (EXPERIENCE x MATERIAL; 2 x 3 ANOVA). This analysis produced a significant main effect for materials only. For specific cognitive actions, the mean score when using principled display materials is significantly different across types of material used [$F_{(2,12)} = 13.623$; $p = .004$]. Figure 6 illustrates this difference and shows that the savings over baseline are greater for principled materials than they are for standard materials. These maintainers, when using principled materials, required only .42 to .76 of the cognitive actions required in the baseline. When using standard materials, these maintainers used 1.40 times as many cognitive actions as the baseline.

Figure 6. Graph comparing the means of materials by experience level for cognitive actions goes about here.

The third analysis examines the value of these displays for saving on the number of displays examined during maintenance problem solving. We analyzed the mean proportion of baseline scores according to experience level and principled material presentation (EXPERIENCE x

MATERIAL; 2 x 3 ANOVA). This analysis produced a significant main effect for material presentation and an interaction effect for experience x material. The mean proportion of baseline scores for displays examined are significantly different across types of material used [$F_{(2,12)}$ = 18.491; $p \leq .001$]. Figure 7 illustrates this difference and shows that the savings over baseline are greater when examining principled display materials than they are when examining standard display materials. These maintainers, when using principled materials, required .25 to .45 as many displays as the baseline. When using standard display materials, they required 1.60 times as many displays as the baseline.

Figure 7. Graph comparing the means of materials by experience level for displays examined goes about here.

The interaction effect reflects a performance difference between experienced and inexperienced maintainers across material presentation [$F_{(2,12)}$ = 5.334; p = .022]. Experienced maintainers examined more displays relative to baseline than inexperienced maintainers when using standard materials. However, when using principled materials, experienced maintainers were much more efficient and showed a greater improvement over baseline than inexperienced maintainers. Although this interaction is interesting, it is difficult to interpret given the small N for the study. One possibility suggests this is due to the fact that experienced people do not normally use standard materials. It will be necessary to examine this in larger studies.

These three analyses provide strong support for the use of displays developed according to the use of the aggregation by abstraction principles. It appears that materials developed to match the level of representation at which maintenance problem solvers are working enable significant savings in the actions carried out and the displays examined during maintenance problem solving. It is tempting to think that this difference might be due to greater reliance on model-based problem solving in the use of principled materials. However, each of the experienced maintainers use model-based processing with the standard materials presentation. Comparison of the mean savings scores on the standard materials presentation for experienced vs. inexperienced maintainers from Table 3 shows no difference. This indicates that model-based problem solving was not the key factor in producing the savings in cognitive activities. Consequently, the displays supported problem solving across strategies, processes, actions, and particular displays.

Concept Formation in Display-based Problem Solving

Data. These are the same data as used in the previous analyses; however, there is a different focus. These data focus on the numbers of different kinds of actions taken when using different display materials for solving problems. Consequently the findings are presented, for each action, as the proportion of baseline actions for a particular problem associated with particular display material. The analysis examines the relationships among these actions, the role they have in concept formation, and the differential effects they might have upon maintenance problem solving.

Findings. The findings illustrate the way in which different cognitive actions occur for problems in which different kinds of displays are examined. We assume that any differences found reflect differences in the underlying concept formation process contributing to maintenance problem solving. To establish whether a difference existed we conducted a MATERIAL x ACTIONS ANOVA (3 x 6) on the mean proportion of baseline as described previously. This analysis showed significant differences among ACTIONS [$F_{(5,90)} = 8.210$; $p \leq .001$] for the number of actions used relative to baseline as well as among MATERIALS [$F_{(2,90)} = 18.174$; $p \leq .001$]. There was no ACTIONS x MATERIALS interaction. Since the interaction was not significant we only examined the inter-MATERIAL differences shown in Figure 8 for trends and insights relative to concept formation and maintenance problem solving.

Figure 8. Graph comparing the means of materials by specific actions for displays examined goes about here.

The general pattern of differences in actions required for solving these maintenance problems is about the same across all the actions for all display materials used. Interesting in the general pattern is that, relative to baseline, maintainers engage in more *identify* actions when solving problems with standard materials than they do when solving problems with materials supporting form, functions, and purpose levels of abstraction relevant to the problem. This trend of more actions required relative to baseline for using standard materials holds up across all actions. However, the amount of change in actions required from standard materials to principled materials appears to be different for *identify, match,* and *look.* For example, on *match* the mean proportion of baseline actions goes from .21 to .13 (standard materials to function-first materials) for a change of .8 while the change is .21 for *look.* These differences suggest differences in the way aggregation by abstraction based displays support concept formation and problem solving. The rest of this section addresses patterns that appear relevant to these differences.

One general pattern is the decrease in actions going from standard displays to function-first displays to purpose-first displays as measured across all actions. Viewed as a whole, this result provides support for the view that these principled displays benefit visual understanding, concept formation, and problem solving as defined in Figure 2 and discussed in previous results. This finding might be confounded by a practice effect, therefore it illustrates several research issues to be clarified. One is whether the improvement from function-first materials to purpose-first materials represents improved processing support or improved display use due to practice. A second question is whether support from the displays is specific to particular action or actions. Third is whether improvements in a particular action propagates improvements elsewhere; or, whether actions are supported directly by the displays without propagating effects to other actions.

Another pattern is the slightly greater improvement for *identify* over all other actions except *look*. Since *identify* corresponds to concept formation of a relevant internal representation then the data suggest that these principled displays do more to support concept formation than for all other processes except visual understanding. This is illustrated in the differences in Figure 8. This finding suggests that with display materials developed according to the aggregation by abstraction principle, fewer *looks* are required to find useful material from which relevant internal representations can be formed. And it appears that some of the diagrams may provide exactly the representation needed by maintainers for problem solving, without having to transform the representation through concept formation.

A final noticeable pattern emerges from examining improvements in *recall*, *identify*, and *match* as compared to *look*. The improvement in *look* is dramatic while the improvement in the other three is moderate. This could happen for two possible reasons. Decreased numbers of *look* might force the problem solver to depend more heavily on other actions than they would have otherwise. This interpretation means that *look* actions constrain the use of other actions. The other possible reason is that increased numbers of *recall*, *identify*, and *match* cause there to be less need for *look*. This interpretation means that other actions enable *look*. This distinction cannot be resolved with these data and will have to be addressed in future studies.

DISCUSSION

This study produced three interesting sets of findings that bear on the original hypothesis. One was the refinement of the cognitive framework for maintenance problem solving. As a result of this study we revised the framework to incorporate cognitive processes and actions comprising those processes. During this refinement we identified a number of different cycles of

actions that carry out the same processes. It appears that these different cycles might be related to different overarching problem solving strategies and the use of information represented differently in the abstraction by aggregation space. This requires further analysis and study that will be carried out at a later date. Our framework and methods provide the tools for subsequent data collection and analyses.

The second set of findings demonstrated the value of using diagrams developed according to principles of aggregation by abstraction for maintenance problem solving. In every analysis, either one or both sets of principled materials demonstrated a significant savings in processes, actions, and displays used over standard materials using manual-dictated procedures. This means that principled materials provided savings for general cognitive processes carried out, specific cognitive actions carried out, and for display materials examined during the course of maintenance problem solving. These savings were even demonstrated by maintainers using principled display materials with manual-dictated procedures (i.e., use the troubleshooting charts).

The third set of findings demonstrated the differential effect of aggregation by abstraction based displays on cognitive actions, in particular concept formation. The findings indicate the value of these kinds of external representations for identifying a relevant internal representation, matching a representation to some element of the problem space such as a rule or model, and remembering a relevant internal representation. In particular the findings revealed three questions that need to be answered in future work. One question concerns the extent to which purpose-first displays supported problem solving over other displays versus how much practice effect there was for the use of principled displays. Another question is how much support the aggregation by abstraction based displays give to a particular cognitive process such as concept formation versus being a general support for all cognitive processes involved in maintenance problem solving. The third question, related to the second, is whether the effect of these displays is to enable some actions as a result of using other actions; or, to constrain some actions as a result of changes in others.

Future studies and analyses will explore the relationships of the principled displays to the particular actions and particular concept representations that maintainers employ during problem solving.

CONCLUSIONS

There were two general goals to this work. One was to develop principles to guide the transformation of hardcopy formats of qualitative and quantitative information to electronically displayed formats. For these studies, the goal was scaled down to the development of initial principles that could be tested on a small scale. The other goal was to evaluate these principles in a realistic context with maintainers of an operational system. The evaluation was aimed at determining whether to continue developing the principles based on our current view or whether to re-evaluate our current view.

Toward the first goal we developed a view of the cognition required for maintenance problem solving. A central aspect of this view is that the key cognitive activity for our purposes is a concept formation process which maps external representations such as diagrams to relevant internal representations such as rules or models. Furthermore, we proposed a structure-mapping mechanism as the means by which concept formation takes place. This structure-mapping transforms a base representation to a target representation by making similarity judgments along levels of aggregation (features) and abstraction (relations among features). As a general principle, we proposed that displays to support maintenance problem solving should vary along these dimensions. To the extent there is a variety of display representations, the maintainer would be more likely to match the right level of representation to specific processing needs.

The initial study supported this view and provided the opportunity to develop a framework of the cognitive activities of the maintainer. To achieve the second goal, a second study was conducted in which principled displays were used by the maintainer for problem solving scenarios. The results for the use of principled displays were compared to those for using standard materials. The use of principled displays led to a significant savings in actions engaged, as coded from the framework, and displays examined by the maintainers.

Use of the aggregation by abstraction information space as a way of operationally defining forms of external representation holds promise for the development of displays supporting maintenance problem solving. Work in the next phase of this project will further operationalize the definitions of the different levels of aggregation and abstraction. Based on this operationalization and further understanding of the specific maintenance domain we will develop a wide range of displays that should be useful to a broader range of maintenance problems. This should allow us to explore not only the utility of displays based on the concepts but also the relation of the displays and the information they contain to the conceptual representations of the maintainers.

This work showed that maintenance problem solvers engage in a clearly definable set of processes and actions. These processes can be examined for the way in which they affect or are affected by information in external displays. So the next phase of this work will also examine in more detail the relationships of the aggregation by abstraction space to cognitive processing in maintenance problem solving. In particular we expect to explore how the *match* and *identify* cognitive actions are carried out. We expect to see that they occur as concept formation and can be modelled by a structure-mapping mechanism. Using this model should allow us to develop and predict the effects of good and poor external representations.

Plans for the future include a series of rigorous, controlled experiments which will explore the issues discussed above. If the promise demonstrated by the aggregation by abstraction information space for supporting concept formation holds up in more rigorous and complex studies then it should not be long before a solid set of principles is available to the development of small displays for maintenance problem solving.

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TABLES

Table 1

Distribution of Tasks among Problems.

	PROBLEM 1		PROBLEM 2		PROBLEM 3		
TASKS	rule-based	model-based	rule-based	model-based	rule-based	model-based	TOTALS
look	8	0	25	0	8	0	41
identify	1	1	2	1	1	1	7
match	0	2	1	2	0	1	6
reason	0	1	0	1	0	0	2
remember	5	6	2	9	7	3	32
locate	6	2	10	4	7	1	30
repair	0	1	0	1	1	3	6
test	7	5	9	9	7	3	40
TOTALS	27	18	49	27	31	12	164

Table 2

Data Definitions.

Dependent Variable	Definition
number of cognitive processes	sum of the frequencies of occurrence of *reason, locate, test* within each problem for each subject
number of cognitive actions	sum of the frequencies of occurrence of *apply, goto, identify, look, match, recall* within each problem for each subject
number of displays examined	sum of the frequencies of displays examined within each problem for each subject

Table 3

Mean Proportion of Baseline Scores for Processes, Actions, and Displays Examined.

Problem Type		Processes	Actions	Displays Examined
Control display material				
Standard display material	M	.882	1.430	1.618
	SD	.345	.431	.855
Experimental display material				
Function material first problem	M	.707	.758	.445
	SD	.450	.353	.211
Purpose material first problem	M	.400	.420	.248
	SD	.342	.294	.246

FIGURES

Figure Caption

Figure 1. The maintenance domain.

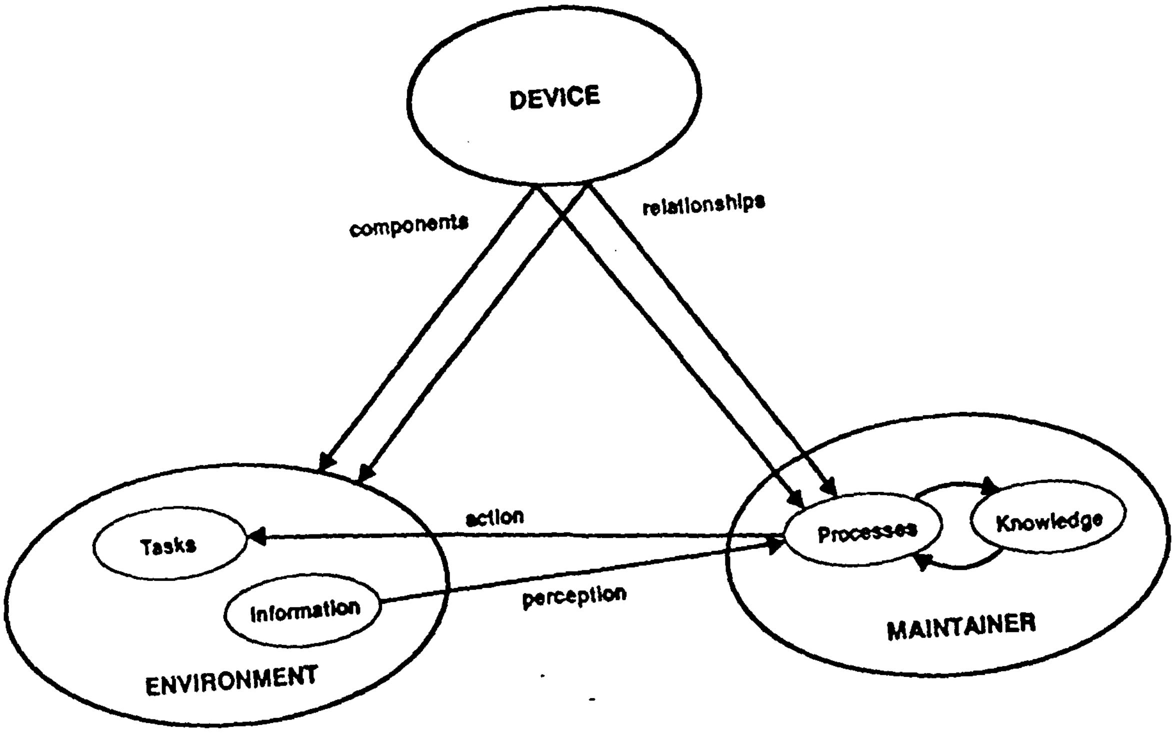

DEVICE
components
relationships
action
Tasks
Information
Processes
Knowledge
perception
ENVIRONMENT
MAINTAINER

Figure Caption

Figure 2. The general cognitive process.

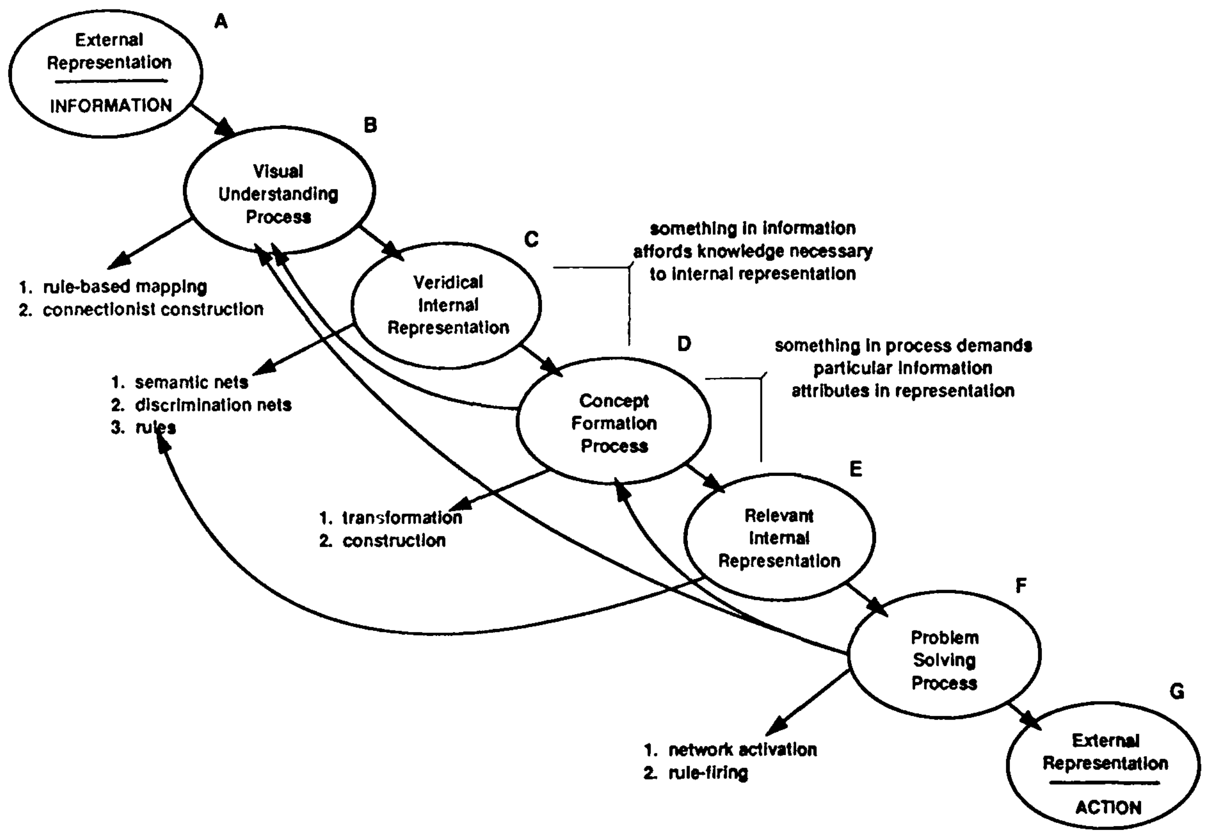
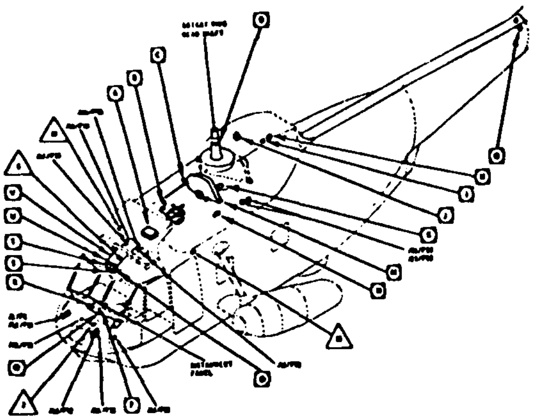
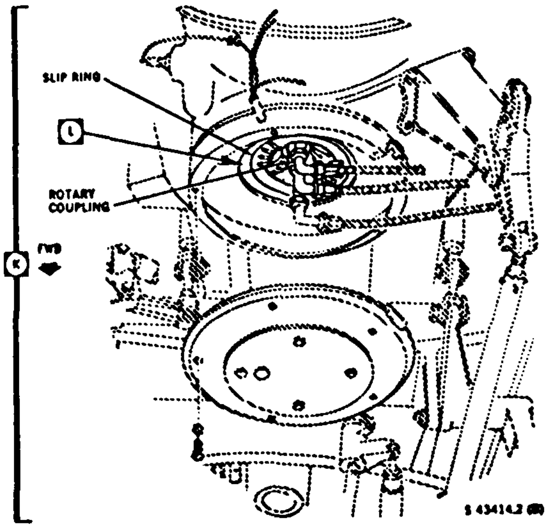

A
External
Representation
INFORMATION
B
Visual
Understanding
Process
1. rule-based mapping
2. connectionist construction
C
Veridical
Internal
Representation
something in information
affords knowledge necessary
to internal representation
1. semantic nets
2. discrimination nets
3. rules
D
Concept
Formation
Process
something in process demands
particular information
attributes in representation
1. transformation
2. construction
E
Relevant
Internal
Representation
F
Problem
Solving
Process
1. network activation
2. rule-firing
G
External
Representation
ACTION

Figure Caption

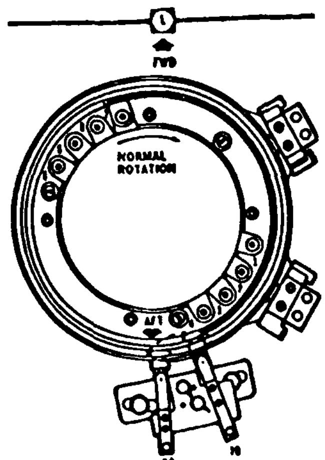
Figure 3. Example of levels of aggregation.



System



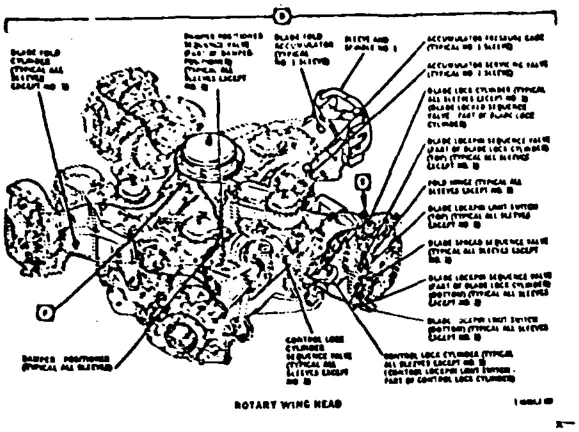
Device



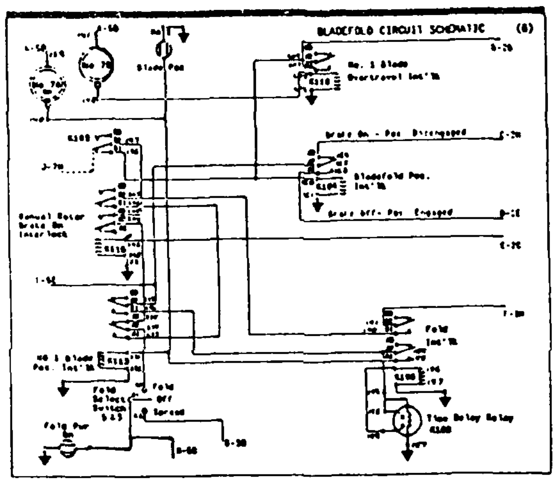
.Component

Figure Caption

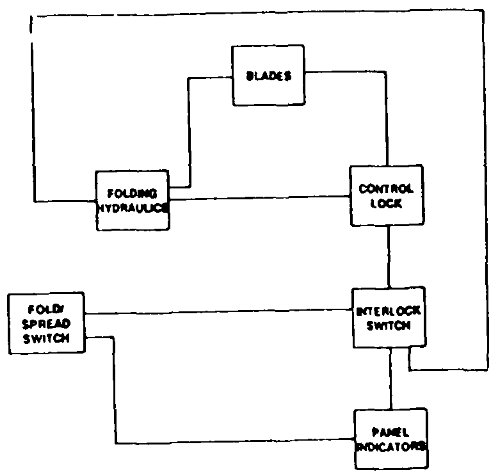
Figure 4. Example of levels of abstraction.



Form



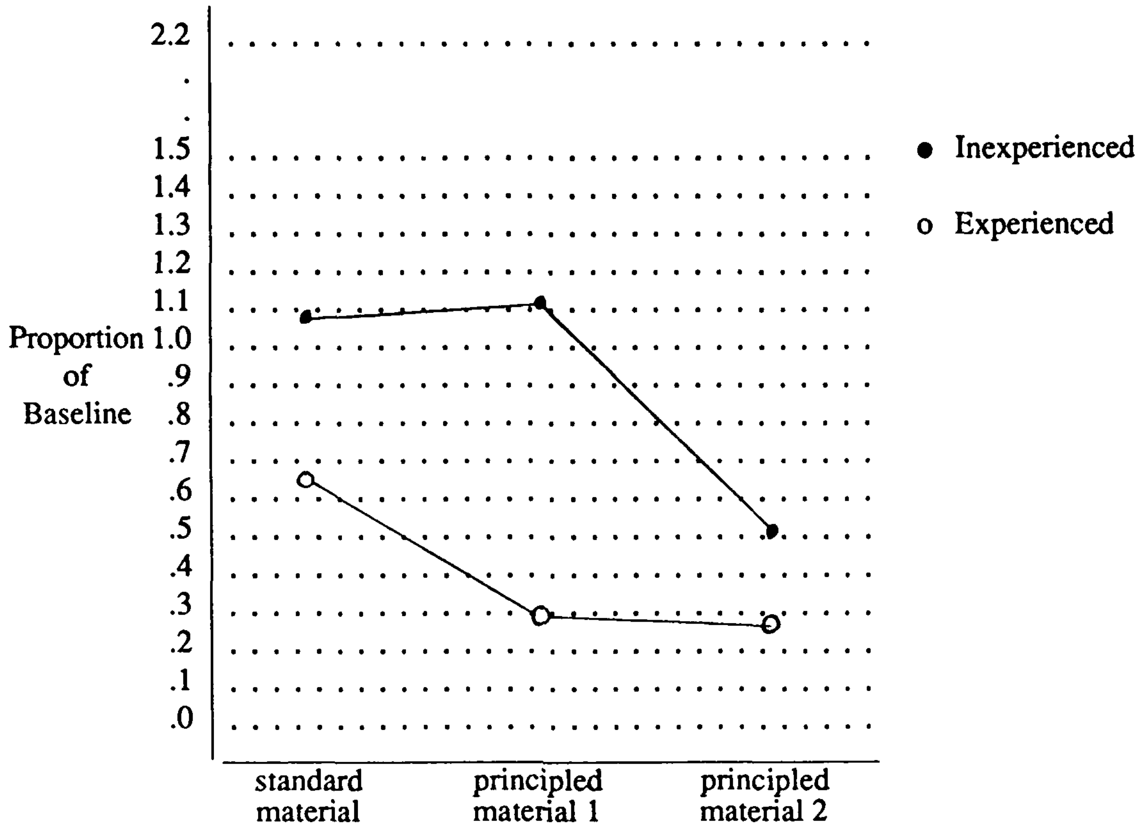
Function



Purpose

Figure Caption

Figure 5. Comparing the mean proportion of baseline scores for general cognitive processes across materials and experience.



2.2
1.5
1.4
1.3
1.2
1.1
Proportion 1.0
of .9
Baseline .8
.7
.6
.5
.4
.3
.2
.1
.0
Inexperienced
o Experienced
standard material
principled material 1
principled material 2

Figure Caption

Figure 6. Comparing the mean proportion of baseline scores for cognitive actions across materials and experience.

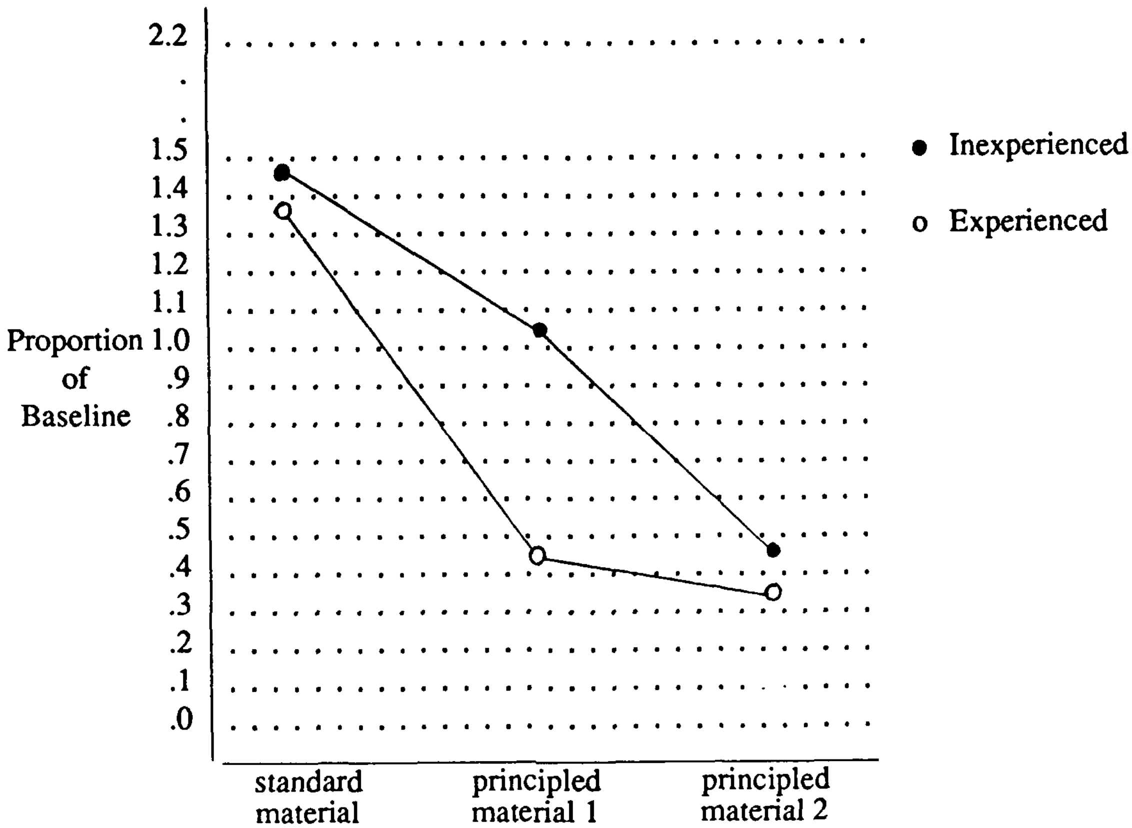

2.2
1.5
1.4
1.3
1.2
1.1
Proportion of Baseline
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
.0
standard material
principled material 1
principled material 2
● Inexperienced
o Experienced

Figure Caption

Figure 7. Comparing the mean proportion of baseline scores for displays examined across materials and experience.

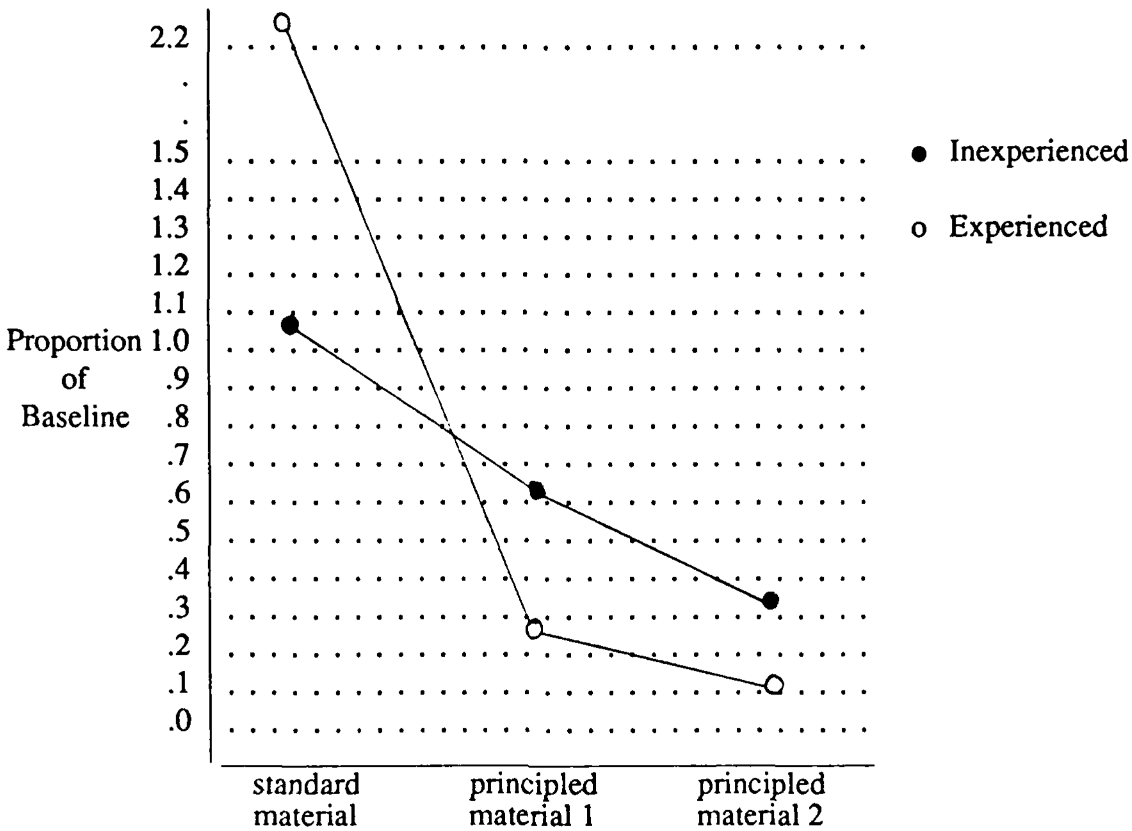
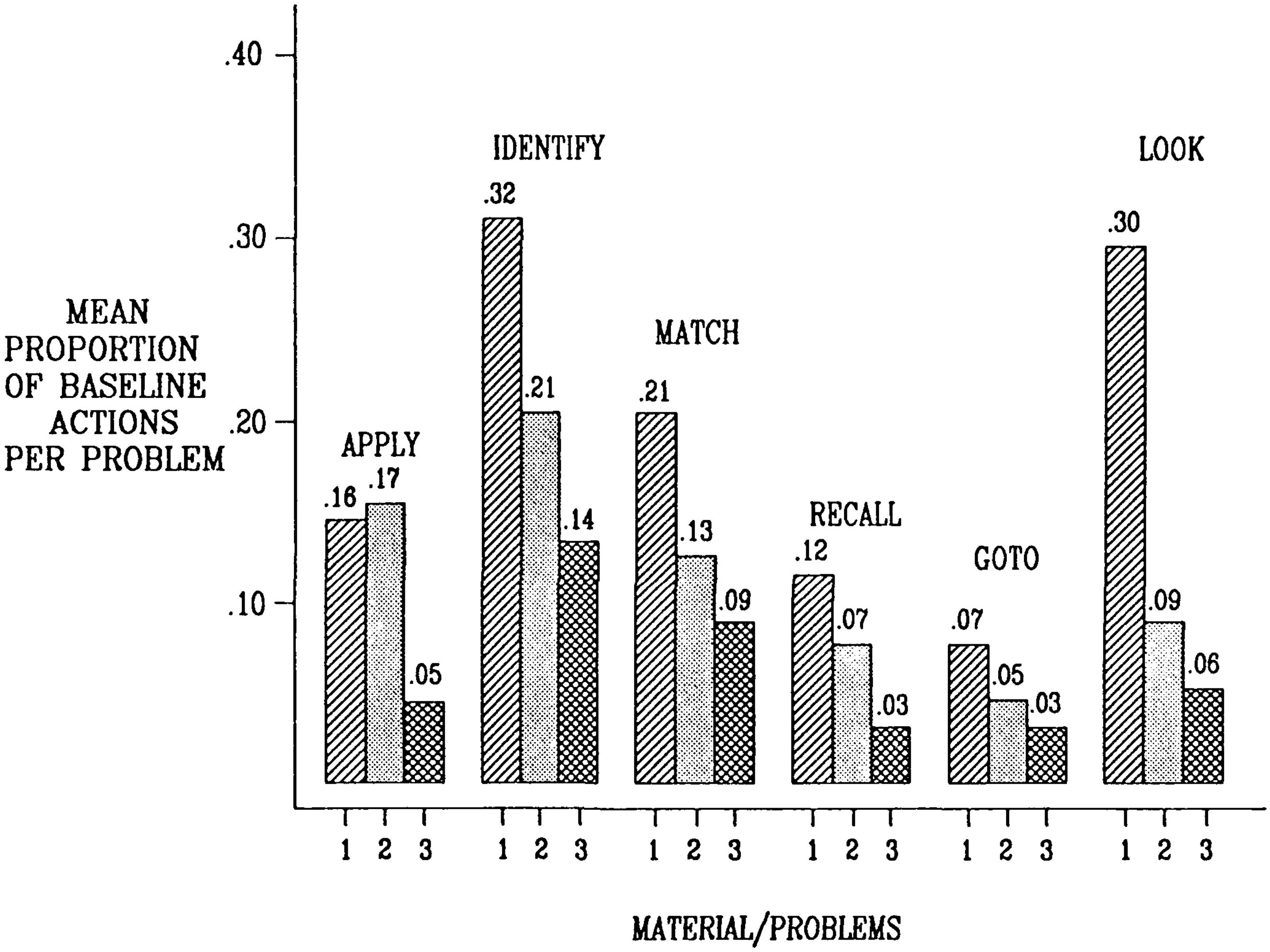

2.2
1.5
1.4
1.3
1.2
1.1
Proportion of Baseline
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
.0
standard material
principled material 1
principled material 2
Inexperienced
o Experienced

Figure Caption

Figure 8. Comparing the means of materials by specific actions for displays examined.



1 = Standard materials

2 = Function-first materials + Form materials

3 = Purpose-first materials + Function materials + Form materials

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